Elements *of* Nuclear Physics

by

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Preface

THE present work originated as an English edition of a volume * written for the Italian *Consiglio Nazionale delle Ricerche* as a part of a general treatise on physics. However, to incorporate recent findings that have resulted from the exceedingly rapid development of nuclear physics during the period of about one year and a half since the Italian text was written, essential modifications have been introduced in the present edition.

The aim of *Elements of Nuclear Physics* is to give, in concise form, a survey of the present status of investigation of nuclear phenomena from the experimental as well as the theoretical point of view. Within the scope of this text could not be included an extensive theoretical analysis of all the problems considered in nuclear physics. Usually, results only have been stated, and these have been given in a form which can be readily comprehended by the non-mathematical reader. Exceptions have been made in several instances; for example, the internal conversion of γ-rays, α-decay, the proton-neutron exchange forces, and the general problem of collisions. In dealing more extensively with these topics, the author has followed closely the treatment given by Professor E. Fermi in his lectures at the University of Michigan during the summer of 1933.

Since it is not only humanly impossible but also fairly impracticable to give a complete bibliography on the subject of nuclear physics, the criterion employed for selection was an attempt to refer only to the most recent and exhaustive papers on each particular problem. References to experiments conducted earlier than 1930 have generally been omitted, since these sources are always available in

* F. Rasetti, *Il Nucleo Atomico*, Zanichelli, Bologna (1936).

the classical works on radioactivity, a list of which is included in the Bibliography at the end of this volume.

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General Introduction

1. The atom and the nucleus. One of the fundamental achievements in the development of chemistry and physics during the eighteenth and nineteenth centuries was the proof that all matter consists of a number of *elements* which conserve their identity through all the possible chemical and physical transformations that they may undergo. Each element was characterized by its *atomic weight*, which determines in what proportions it combines with other elements to form chemical compounds. Mendeleew showed that the elements, considered in the order of increasing atomic weight, manifested characteristically periodical physical and chemical properties, which could be most clearly represented by arranging the elements themselves in a *periodic table.*

During the end of the nineteenth and the beginning of the twentieth century, much knowledge was gained from the investigation of the electrical properties of matter. The study of the discharge through rarified gases and the consequent discoveries of the cathode rays, the positive rays, and the X-rays showed that matter was intimately connected with positive and negative electric charges. While the atomic hypothesis emerged from the stage of speculation to one of surprising reality through the investigation of Brownian motion, radioactivity, and many other phenomena, it appeared at the same time that the atom did not constitute the ultimate and indivisible unit of matter, but was built up of positively and negatively charged particles which, under certain conditions, could be separated.

In regard to separation, negative and positive electricity showed essentially different behavior. Negative electricity appeared to be associated with corpuscles of very small mass —thousands of times smaller than the atomic masses—and always identical in mass and charge, no matter from what element they had been separated. This particle was called the *electron*. Positive electricity, on the other hand, appeared always to be associated with particles of atomic mass and characteristic of the element from which they had been extracted.

All of these problems received a complete explanation through Rutherford's formulation of his *nuclear model* for the atom, and the subsequent work of the first quarter of the twentieth century. We know now that the atom consists of a central heavy particle, or *nucleus*, in which most of the mass and the total positive electric charge are concentrated. Around the nucleus move a certain number of electrons whose total negative electric charge exactly compensates the charge of the nucleus, giving rise to a neutral atom. The charge of the nucleus, which is thus an integral multiple Z of the electronic charge and determines the number of electrons, is the essential factor that distinguishes one element from another, and increases by one unit in proceeding from one element to the next in the periodic table—going from one (hydrogen) to ninety-two (uranium). Z is called the *atomic number*.

To explain the behavior of the electrons in the atom, the new concepts of the *quantum theory* had to be substituted for the principles of classical mechanics and electrodynamics. The application of the quantum theory to the atom began with Bohr's theory of the hydrogen atom (1913) and reached a highly perfected form in the new quantum mechanics, developed through the fundamental work of Bohr, Heisenberg, Pauli, De Broglie, Schroedinger, Dirac, and many others (1913–1927).

The experimental basis for this development was the observation that an atom can exist only in certain generally discrete states of motion, called the *quantum states* or *stationary states*, having characteristic energies or *energy levels* E_i; and that it can pass from one state to another by the emission or absorption of monochromatic radiation in the form of a *light quantum*, or *photon*, whose energy is equal to $E_i - E_k$ and is connected with the frequency ν_{ik} through Bohr's relation:

$$E_i - E_k = h\nu_{ik}$$

Here h represents Planck's constant.

Within the limits of this text we cannot review, even briefly, the wide field of application and the results of the quantum theory of the atom. It will suffice to recall that by means of this theory we now have a consistent mathematical scheme which accounts for all spectroscopic phenomena in the optical and X-ray regions, and, at least in principle and apart from mathematical difficulties, for the behavior of the elements in forming molecules and crystals. In particular, the structure of the periodic system of the elements results naturally from a consideration of the possible quantum states of the electrons in the atom and from Pauli's *exclusion principle*, which prevents more electrons from occupying a single quantum state. Even the intrinsic angular momentum, or *spin*, of the electron, which Uhlenbeck and Goudsmit introduced in order to obtain the correct number of quantum states for the electrons in the atom, was shown by Dirac to be a necessary consequence of a correct relativistic wave equation.

Through all of this development of atomic physics the nucleus pláyed a rather unimportant role, as its internal structure remained unaffected in all ordinary physical and chemical processes, and it was sufficient to consider the nucleus as a point particle with a certain electric charge and a certain mass. The fact has been recognized, however, that changes in the internal structure of the nucleus actually take place in a particular class of phenomena—that is, in *radioactivity;* but these phenomena remained little accessible to experimental investigation and almost closed to theoretical analysis until very recent years. Hence they did not interfere with the main line of development of the quantum theory of the atom. However, since these phenomena constitute the subject matter of this book, we must now turn our attention to the main facts of radioactivity.

2. Radioactivity. Radioactive phenomena were discovered when Becquerel (1896) observed that uranium salts emitted radiations of a new kind, which were capable of going through layers of matter completely opaque to light and which could be detected by their properties of ionizing gases and of blackening photographic plates. An extremely important advance in this field was due to the celebrated investigations of P. and M. Curie, who proved that most of the activity of uranium belonged to other elements present in exceedingly small amounts. These elements, when isolated in a pure state, showed the phenomenon of radioactivity with enormously higher intensity. The best-known of such elements was radium (Curie, 1898).

Further investigation of these rays led to their classification into three clearly defined groups, called α, β, and γ. Their characteristics are described in the following paragraphs.

α-rays. Strongly ionizing and weakly penetrating radiations (completely absorbed by a sheet of paper), deflected by a magnetic and electric field as positively charged particles. Further analysis has proved the particles to be doubly charged helium atoms (ions).

β-rays. More penetrating than the α-rays (capable of going through a few millimeters of aluminum), less strongly ionizing, deflected by electric and magnetic fields as negatively charged particles. These particles consist of high speed electrons, similar to those produced in the cathode rays.

γ-rays. Highly penetrating and weakly ionizing radiations, undeflected by electric or magnetic fields. These rays represent a high frequency electromagnetic radiation—that is, they have the same nature as the X-rays.

The complete failure of attempts to influence radioactivity by any physical or chemical agents has indicated that it does not originate in the regions of the atom which are affected by ordinary physical and chemical phenomena. When Rutherford, through experiments on the scattering of α-particles (1911), discovered the nuclear structure of matter, it became natural to consider the radioactive phenomenon as a process taking place in the nucleus itself.

Before this time the relation between the radiation emitted and the change effected in the nature of the emitting atom had been partly explained through the fundamental work of Rutherford and Soddy (1908). Now we can express these results in a simple form by means of the following *displacement law:* By the emission from the nucleus of an α-particle (charge 2, mass 4), the atomic number of the element is decreased by two units, and the atomic weight by four; by the emission of a β-particle (charge -1, very small mass), the atomic number is increased by one unit and the atomic weight is practically unchanged. Thus radioactivity, unlike any other natural phenomenon, results in a permanent change of one element into another.

Generally a number of transformations (*radioactive series*) take place one after another, until a stable product is eventually reached. Sometimes, by a succession of one α-transformation and two β-transformations, the element is brought back to its original place in the periodic system; however, its atomic weight is then smaller by four units. These two elements, occupying the same place in the periodic system but being different in mass and in radioactive properties, are called *isotopes*. Most of the ordinary inactive elements have been shown to consist of a mixture of isotopes.

If we now consider the time dependence of the process of radioactive disintegration, we find, again, peculiar characteristics that accentuate the differences in the nature of radioactive and other physical phenomena. The facts can be summarized by the following simple law: The number of atoms of a radioactive substance which disintegrate in the very short time dt is proportional to the number N of the existing atoms, and is independent of any physical and